Fuel Economy Impacts of Manual, Conventional Cruise Control, and Predictive Eco-Cruise Control Driving

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ABSTRACT
The paper presents the results of a field experiment that was designed to compare manual driving, conventional cruise control (CCC) driving, and Eco-cruise control (ECC) driving with regard to fuel economy. The field experiment was conducted on five test vehicles along a section of Interstate 81 that was comprised of ±4% uphill and downhill grade sections. Using an Onboard Diagnostic II reader, instantaneous fuel consumption rates and other driving parameters were collected with and without the CCC system enabled. The collected data were compared with regard to fuel economy, throttle control, and travel time. The results demonstrate that CCC enhances vehicle fuel economy by 3.3 percent on average relative to manual driving, however this difference was not found to be statistically significant at a 5 percent significance level. The results demonstrate that CCC driving is more efficient on downhill versus uphill sections. In addition, the study demonstrates that an ECC system can produce fuel savings ranging between 8 and 16 percent with increases in travel times ranging between 3 and 6 percent. These benefits appear to be largest for heavier vehicles (SUVs).

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1. INTRODUCTION

This section quantifies the fuel efficiency impacts of using a conventional cruise control (CCC) system relative to manual driving based on field driving tests. CCC (or autocruise) is a device or system that is frequently used while driving, especially on highways, as it automatically controls the speed of a vehicle as set by the driver. Consequently, using CCC reduces the driver's fatigue and improves comfort. As fuel prices change significantly, the fuel savings that result from the use of CCC have recently attracted attention. From a fuel-saving perspective, CCC use is recommended as one of the eco-driving tips by many organizations.

CCC was invented in 1945 by Ralph Teetor, and the system was initially installed into the Chrysler Imperial in 1958 [1]. Automotive electronic CCC, which is an electrical version of the CCC, uses digital memory and was invented by Daniel Aaron Wisner in 1968. An extensive adaptation of CCC was achieved following development by Motorola, Inc. of an integrated circuit. Most cars currently manufactured in the United States are fitted with a CCC system that uses a specific control algorithm that depends on the manufacturer.

As mentioned earlier, it is widely known that the use of CCC on highways can save gas. However, it is difficult to find literature that proves CCC's effectiveness in a quantitative manner with regard to fuel savings even though this idea seems to be accepted by the public. One study conducted by Edmunds.com concluded that an average fuel economy saving of 7 percent could be achieved from the use of CCC [2]. However, it is not clear how the effectiveness will vary if the system is used on uphill or downhill sections. It is recommended that CCC be disabled on hilly terrain because the system tries to maintain even speeds on steep hills, thus resulting in high fuel consumption levels [3]. The literature indicates that experienced drivers can manually drive in a more fuel-efficient manner than by enabling CCC driving [4]. Consequently, there is a need to test the effectiveness of using CCC in a systematic fashion based on field driving tests. Specifically, the objectives of this study are to test:1) if CCC driving can significantly save fuel compared to manual driving, and 2) whether fuel savings remain constant when driving on uphill and downhill sections of a roadway. In addition, the third objective is to compare the operation of a predictive ECC system to manual and CCC driving.

2. INTRODUCTION

2.1. Collection of Field Data

Experiments were conducted on a section of Interstate 81 between mile markers 118 and 132 in order to collect fuel consumption rates under actual driving conditions. The test section was selected because it comprises various uphill and downhill sections and thus provides a suitable environment to test different engine load conditions under manual and CCC driving scenarios. Specifically, the northbound and the southbound directions can be considered a 1.3% downhill and a 1.3% uphill section, respectively, as the difference in altitude between the start and end points of the section is approximately 280 m across 22.4 km (14 miles). However, the roadway grade on the section varies between ± 4%. There are two 4% uphill sections that have an additional truck-climbing lane.

Six light-duty vehicles were tested, including four passenger cars and two sport utility vehicles (SUVs). These vehicles included: a 2001 SAAB 95, a 2006 Mercedes

R350, a 2008 Chevy Tahoe, a 2007 Chevy Malibu, a 2008 Chevy Malibu Hybrid, and a 2011 Toyota Camry. The six vehicles were selected to test different manufacturers, model years, and types. The Chevy Tahoe is the heaviest and most powerful vehicle while the Malibu is the lightest and least powerful car. The SAAB 95 is the oldest car and has a turbocharged engine so it generates relatively more power than the other passenger cars when considering their engine sizes.

For the collection of vehicle operation variables and fuel consumption rates an OBD II reader (the DashDaq XL device that is manufactured by Drew Technologies, Inc.) was used. The DashDaq can be easily attached to a window using a shield mount and can log and save up to 16 user-defined parameters [5]. This study selected the following 16 signals to record: absolute throttle position, fuel economy across distance, engine speed, vehicle speed, acceleration level, vehicle power, GPS-calculated speed, latitude, longitude, torque, calculated mass air flow, altitude, air flow rate from mass air flow, accelerator pedal position, fuel economy over time, and fuel level. The signals were saved to a Secure Digital (SD) card with a timestamp. The vehicle signals continued to be displayed on the screen as they were being saved to the card.

Given that the DashDaq provides the fuel economy in units of miles per gallon (MPG) along with a timestamp, instantaneous fuel consumption rates can be calculated from the recorded data. Specifically, the DashDaq calculates the fuel economy using the vehicle speed and mass air flow signals together with two assumptions. The first assumption is that the stoichiometric ratio, also called air-fuel ratio, is 14.7. The density of fuel is assumed to be 720 grams per liter. The fuel economy can then be calculated using Equation (1). Note that the first assumption is not 100% accurate given that the air-fuel ratio does not remain constant and can vary depending on the required power levels. In other words, it does not capture fuel-rich and fuel-lean conditions accurately, so the fuel estimation from this approach may slightly deviate from the true value.

$$FE = \frac{vsd}{a} \tag{1}$$

Where *FE* is the fuel efficiency in MPG, v is the velocity of the vehicle in miles per hour (mph), s is the stoichiometric ratio, d is the density of fuel in grams per gallon, and a is the mass air flow in grams per hour.

The experiments were conducted during off-peak hours between 9 a.m. and 3 p.m. in order to reduce conflicts with other vehicles and secure freedom of driving. Each vehicle was driven 10 times (circulations between mile markers 118 and 132) by two different drivers: five times with the CCC enabled and five times with the CCC disabled. Consequently, four data sets were obtained for each vehicle: the northbound with and without CCC enabled and the southbound with and without CCC enabled. There was an exception with the Toyota Camry due to a roadway maintenance event. Only six circulations were completed, and the last of the experiments could not be conducted due to the limited use of the roadway. The drivers participating in the study were educated about the overall procedures before the experiments. Specifically, the drivers were directed to maintain the highway speed limit of 65 mph in a typical driving manner while the CCC was not used (manual). However, some deviations from the target speed were allowed as needed in order to secure the driver's safety. For the CCC driving experiments, the target speed was also set to 65 mph. The drivers were allowed to turn off the CCC system for their safety as needed.

The specifications of the test vehicles were gathered using publicly available data sources, which included the vehicle manuals, the official sites of the vehicle manufacturers, and other car review sites [3]. Additionally, information about the vehicles was retrieved using the vehicle identification numbers (VINs) [6]. The specification information collected from different data sources was verified before calibrating the coefficients of the Virginia Tech Comprehensive Power-based Fuel Model (VT-CPFM). For cases in which the specifications could not be obtained from the aforementioned sources, typical values were used during the calibration [7]. These included the coefficients of roadway friction and the coefficients of rolling resistance.

The specifications that were used to calibrate the VT-CPFM models are shown in Table 1 along with the data sources. The VT-CPFM parameters were calibrated using a

Table 1. Specifications of the Test Vehicles

Description	Saab 95	Mercedes R350	Tahoe	Malibu	Malibu Hybrid	Camry	Source
Trim	4dr Sedan	base Base	LS 2WD	LS	Base	LE	
Model Year	2001	2006	2008	2007	2008	2011	
Wheel Radius	0.32145	0.36865	0.4014	0.32375	0.3322	0.3322	
Redline RPM	6000	6400	7000	6000	6000	6300	
Drag Coefficient	0.29	0.31	0.39	0.34	0.34	0.28	
Frontal Area (m2)	2.288	2.911	3.456	2.318	2.313	2.424	
Wheel Slippage	0.035	0.035	0.035	0.035	0.035	0.035	
Number of Cylinders	4	6	8	4	4	4	
Engine Size (L)	2.3	3.5	5.3	2.2	2.4	2.5	
Number of Gears	4	7	4	4	4	6	
First-gear Ratio	3.67	4.38	3.06	2.96	2.96	3.54	Auto
Second-gear Ratio	2.1	2.86	1.63	1.62	1.62	2.05	website
Third-gear Ratio	1.39	1.92	1	1	1	1.38	
Fourth-gear Ratio	1	1.37	0.7	0.68	0.68	0.98	
Fifth-gear Ratio	–	1	–	–	–	0.74	
Sixth-gear Ratio	–	0.82	–	–	–	0.66	
Seventh-gear Ratio	–	0.73	–	–	–	–	
Final Drive Ratio	2.56	3.9	3.23	3.63	3.63	3.82	
Mass (kg)	1601	2190	2388	1440	1604	1500	
City Fuel Effi. (mpg)	21	16	14	24	24	22	
Hwy Fuel Effi.(mpg)	30	21	20	34	32	33	Rakha
Rolling Coef. (C_r)	1.75	1.75	1.75	1.75	1.75	1.75	et al.,
c_1	0.0328	0.0328	0.0328	0.0328	0.0328	0.0328	2001
c_2	4.575	4.575	4.575	4.575	4.575	4.575	
Driveline Effi.	0.92	0.92	0.92	0.92	0.92	0.92	
P_{mfo} (Pa)	400000	400000	400000	400000	400000	400000	Wong,
Q (J/kg)	43000000	43000000	43000000	43000000	43000000	43000000	2001
Idling Speed (rpm)	820	700	600	680	660	660	Field Data

calibration tool that was developed in the MATLAB environment and described in detail in the literature [8].

3. COMPARISON OF MANUAL AND CCC DRIVING TESTS

3.1. Speed and Throttle Control

The field test results show that the CCC systems demonstrated a good ability to maintain a constant speed. Overall, the systems maintained the vehicle speed close to the target speed of 65 mph during most of the test runs. As shown in Figure 1 (which includes some sample speed profiles from the test runs), the speeds of the individual vehicles were maintained close to the target speed with marginal errors. However, it is interesting to note that the control logics of the systems are distinct from each other. Figure 1(c) clearly shows that the Chevy Tahoe, which is the heaviest car amongst the test vehicles, accelerated on the downhill sections and returned to the target speed after passing the downhill sections. Additionally, the Toyota Camry CCC system also seems to have similar control logic to the Tahoe although the speed does not increase as much as that of the Tahoe. The speed profiles of the Chevy Tahoe and the Toyota Camry are different from the speed profiles of the other systems while driving on the downhill sections. Specifically, the Chevy Tahoe and the Toyota Camry systems seem to allow the vehicle to utilize their gravitational force, which might affect fuel economy rather than braking to maintain the target speed.

Conversely, the drivers of the test vehicles were capable of manually maintaining the target speed. However, it was observed that manual driving does not generally control the speed as precisely as a CCC system, as is demonstrated in Figure 2. The deviations of the manual driving test runs from the target speed appears greater than those of the CCC test runs. This fact is confirmed by the higher speed standard deviations associated with manual driving. However, it is demonstrated that some of the drivers manually achieved more precise control of the target speed than when using the CCC system. For example, based on the test results of the Toyota Camry, the standard deviation of the CCC driving tests on the southbound lanes was greater than that of the manual driving tests, as can be seen in Table 2.

With regard to throttle control, one would expect that the CCC throttle control would be more stable than manual control (i.e., without significant abrupt changes in throttle levels) when compared to manual driving. Figure 3(a) clearly demonstrates that Driver-1 frequently alternated between pressing the accelerator pedal and the brake pedal, especially when driving on the uphill and downhill sections. Consequently, it appears that Driver-1 was not as skilled as the other drivers in controlling the vehicle throttle. Interestingly, the throttle control profiles of the Driver-1 manual and CCC driving tests were similar to each other in the sense that the general patterns of throttle positions were identically sensitive to the gradients of the roadway. However, they are clearly distinct because the manual driving test had greater throttle positions. This is one of the critical reasons why using the CCC systems generally produced fuel savings. In terms of fuel economy, it was observed that the fuel economy values of the CCC and manual driving tests plotted in Figure 3(a) were 21.3 MPG and 20.4 MPG, respectively. Thus, using CCC for Driver-1 resulted in a 3-percent increase in vehicle mileage when compared to manual driving. Figure 3(b) is a profile of a different driver (Driver-2) who experienced the identical experimental setting as Driver-1. As can be seen, the Driver-2 throttle control was better than that of Driver-1 since the peaks in the throttle positions were generally lower than those of Driver-1.

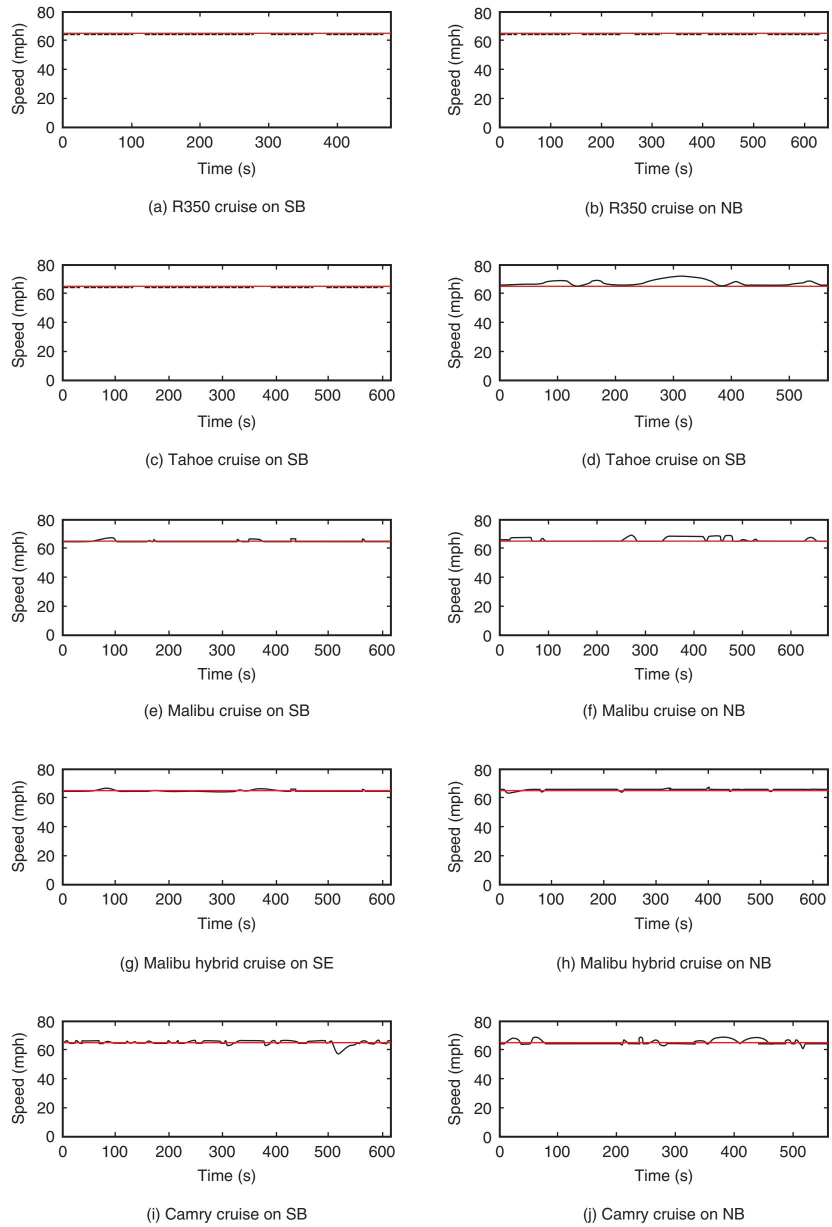

Figure 1. Speed Profiles for CCC Driving

There was another interesting result found with regard to throttle control. There may be several factors contributing to the throttle position controlled by the CCC systems, such as vehicle specification, driving environment, CCC logic, etc. However, it can be confirmed that the throttle control logic is one of the most critical factors that

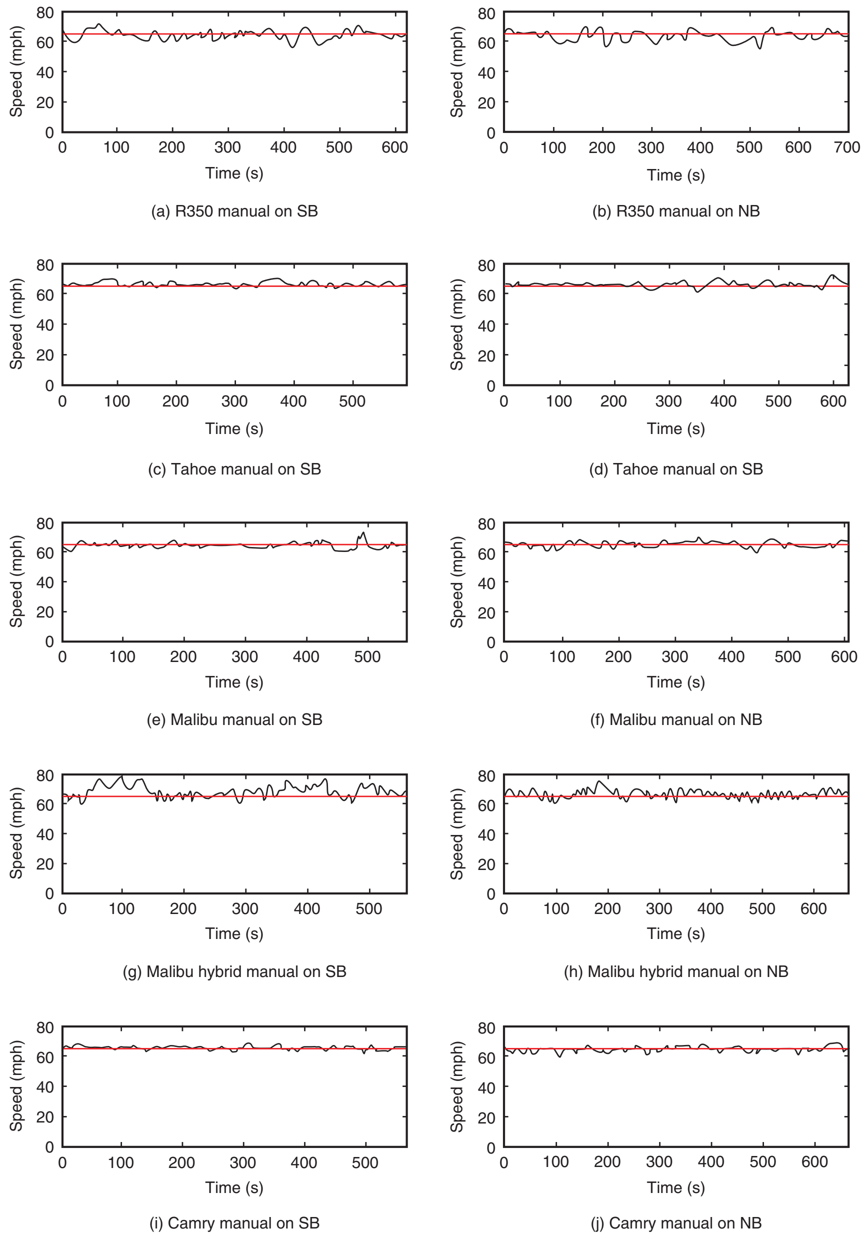

Figure 2. Speed Profiles for Manual Driving

results in differences in the throttle positions. As can be seen in Figure 4, the Toyota Camry and Chevy Malibu ideally maintained the target speed of 65 mph during a test run, but the throttle position profiles of the two vehicles were clearly distinct from each other.

Table 2. Average Speed (km/h) and Standard Deviation of the Speed Measurements

Classification		Southbound Manual	Southbound CCC	Northbound Manual	Northbound CCC
Mercedes R350	Avg. Speed	102.8	102.8	102.8	101.9
	Std. Dev.	4.2	0.6	3.9	2.9
Chevy Tahoe	Avg. Speed	104.7	104.9	105.3	106.7
	Std. Dev.	2.7	2.0	3.4	4.5
Chevy Malibu	Avg. Speed	102.7	104.9	104.7	104.7
	Std. Dev.	4.0	2.3	3.0	3.5
Hybrid Chevy Malibu	Avg. Speed	103.9	103.9	103.9	104.1
	Std. Dev.	5.6	2.3	5.1	2.8
Toyota Camry	Avg. Speed	103.7	103.0	103.3	105.4
	Std. Dev.	2.7	3.5	3.0	3.0

3.2. Fuel Economy

The test results clearly demonstrate that using the CCC system results in a fuel economy enhancement. As can be seen in Table 3, the fuel economy values for the CCC driving tests were greater than those for the manual driving tests, although there were some variations in the differences depending on the driver, the vehicle, and the direction of travel. The average fuel economy enhancement across all the field tests was 3.3 percent. It is interesting to note that using CCC on the northbound section, which is mostly downhill, resulted in better fuel economy than using it on the southbound section, which was mostly uphill. Another interesting finding was that the fuel economy enhancement ranged from 0.2% to 10.5%, demonstrating that changes in driving behavior significantly affect the vehicle fuel economy.

Based on the test results, manual driving and CCC driving were not significantly different from each other with regard to travel times, as demonstrated in Table 3. The relative differences ranged from -2.0% to 1.4%. Consequently, it can be concluded that using CCC devices can save a significant amount of fuel without an impact on travel times.

As illustrated in Figure 3, some differences were found in the throttle control levels between the various drivers. Figure 3 demonstrates that Driver-2 drove more efficiently with regard to fuel savings when compared to Driver-1. In order to assess the differences between the drivers, a comparison of fuel consumption by the different drivers was conducted, and a summary of the results is presented in Table 4. Specifically, the fuel consumption values in Table 4 were computed by averaging all test runs by the individual drivers; in some cases, the values were averaged across more than one test vehicle. As is clearly seen, the average difference between the CCC and manual driving tests of Driver-1 was greater than that of Driver-2. Driver-3 was the most skilled driver amongst the subjects as the manual driving of Driver-3 resulted in less fuel consumption than the CCC driving. This confirms the fact that skilled driving can produce fuel consumption savings relative to CCC driving, as has been demonstrated in the literature [4].

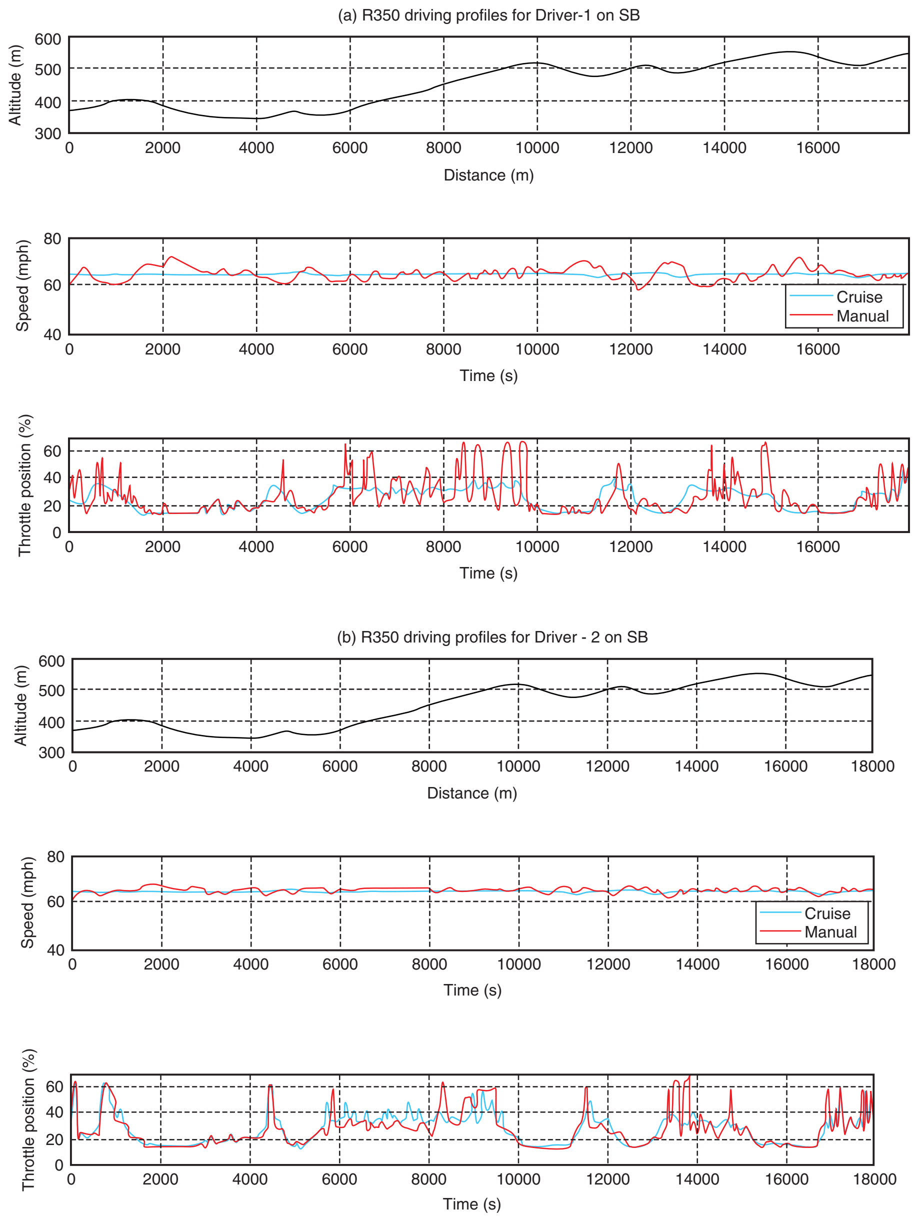

Figure 3. Throttle Profiles

3.3. Statistical Analysis

The field-measured data demonstrate that CCC driving is significantly effective with regard to fuel savings when compared to manual driving. A set of t-tests were then conducted at a 5-percent significance level (alpha = 0.05) to test if CCC driving was

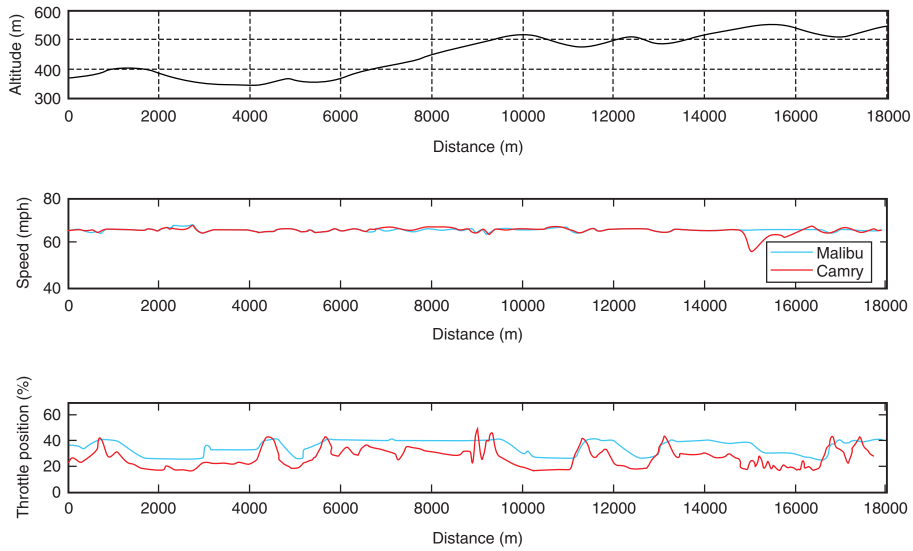

Figure 4. Cruise Control Profiles of Malibu and Camry

Table 3. Average Speed (km/h) and Standard Deviation of the Speed Measurements

	Southbound			Northbound		
Classification	Manual (MPG)	Cruise (MPG)	Relative Diff.	Manual (MPG)	Cruise (MPG)	Relative Diff.
Mercedes R350	20.4	21.0	3.0%	32.0	35.3	10.5%
Chevy Tahoe	18.8	18.8	0.2%	32.2	33.6	4.5%
Chevy Malibu	29.6	30.8	3.8%	46.0	46.7	1.7%
Hybrid Chevy Malibu	27.5	27.7	0.7%	41.0	43.5	6.0%
Toyota Camry	30.1	30.5	1.5%	48.4	49.7	2.8%
Average	25.3	25.8	1.9%	39.9	41.8	4.7%

Travel Time Comparison

	Southbound			Northbound		
Classification	Manual (s)	Cruise (s)	Relative Diff.	Manual (s)	Cruise (s)	Relative Diff.
Mercedes R350	616	616	0.0%	680	678	–0.3%
Chevy Tahoe	605	613	1.4%	657	647	–1.4%
Chevy Malibu	611	604	–1.1%	660	658	–0.4%
Hybrid Chevy Malibu	610	615	0.8%	665	664	–0.1%
Toyota Camry	611	615	0.7%	669	656	–2.0%
Average	611	613	0.4%	666	661	–0.8%

Table 4. Fuel Consumptions (L) by Test Vehicle Drivers

	Northbound			Southbound		
Driver Index	Cruise	Manual	Diff (%)	Cruise	Manual	Diff (%)
1	1.35	1.48	9%	1.98	2.07	5%
2	1.29	1.37	7%	2.01	2.08	3%
3	1.22	1.19	–2%	1.83	1.8	–1%
4	1.35	1.43	6%	2.28	2.18	–4%
5	0.94	0.97	3%	1.36	1.38	2%
6	1.07	1.15	8%	1.53	1.53	0%
7	1.07	1.12	4%	1.58	1.54	–3%

Table 5. T-Test Results

	Southbound			Northbound		
		Confidence Interval (L)			Confidence Interval (L)	
Classification	P-value	Lower Bound	Upper Bound	P-value	Lower Bound	Upper Bound
Mercedes R350	0.00	0.03	0.11	0.01	0.05	0.21
Chevy Tahoe	0.68	–0.21	0.15	0.02	0.01	0.10
Chevy Malibu	0.09	–0.01	0.11	0.97	–0.10	0.09
Hybrid Chevy Malibu	0.65	–0.09	0.06	0.04	0.01	0.12
Toyota Camry	0.31	–0.04	0.09	0.25	–0.03	0.07

statistically different from manual driving. Since fuel economy is sensitive to vehicle specifications and roadway conditions, the field test results (fuel consumption in liters) were classified by vehicle and roadway section and used during the t-tests. Based on the t-test results, it was demonstrated that CCC driving is not, statistically, 100% different from manual driving, as can be seen in Table 5. In the case of the Mercedes R350, the difference between CCC and manual driving was significantly different on the southbound and northbound sections. The differences between CCC and manual driving were more evident on the northbound section. Overall, CCC driving appears to be effective with regard to fuel savings, although the differences between CCC and manual driving are not statistically significant for all test vehicles.

Additionally, a multiple linear regression model was fit to the data in order to gain insight into the relationship between the fuel use and other contributing factors. The framework of the regression model is formulated in Equation (2).

$$y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D \tag{2}$$

Where βs are the coefficients, A is binary variable reflecting the driving classification (CCC or manual driving), B is the vehicle classification, C is the roadway section classification (southbound or northbound), and D is the driver classification.

Given that the dependent variables are non-numerical and qualitative variables, one of the categories of the dependent variables is used as the reference level. For example,

Table 6. Coefficients of the Regression Model and Significances of the Coefficients

	Classification	Estimate	Std. Error	t-value	p-value
β0	Intercept	0.838807	0.038179	21.971	< 2e-16
β1	CC	–	–	–	–
	Manual	0.033761	0.023924	1.411	0.16208
β2	Mercedes R350	0.542127	0.04927	11.003	< 2e-16
	Chevy Tahoe	0.679716	0.05998	11.332	< 2e-16
	Chevy Malibu	0.036807	0.043883	0.839	0.404102
	Hybrid Chevy Malibu	0.186299	0.049265	3.782	0.000299
	Toyota Camry	–	–	–	–
β3	Southbound	0.569075	0.023284	24.44	< 2e-16
	Northbound	–	–	–	–
β4	Driver-1	0.057996	0.050551	1.147	0.254689
	Driver-2	–	–	–	–
	Driver-3	0.049436	0.043087	1.147	0.254661
	Driver-4	–0.01282	0.065927	–0.194	0.846355
	Driver-5	–	–	–	–
	Driver-6	–0.00605	0.049867	–0.121	0.903774
	Driver-7	–	–	–	–

Toyota Camry is used as the reference level of the B classification because "c" comes first in the alphabet. Given that the regression model has a multiple R-squared of 0.9349 and the p-value is less than 2.2e–16, the model is demonstrated to be significant and provides reliable estimates. The regression model demonstrates that manual driving consumes an average of 0.03 L more on the study sections than does CCC driving, as can be seen in Table 6. However, this difference is not significant at the 5% significance level because the p-value of the $\beta 1$ coefficient of the manual driving is 0.16. For the vehicles, the Mercedes R350, the Chevy Tahoe, and the Hybrid Chevy Malibu are significantly different from the Toyota Camry with regard to fuel consumption on the study sections. Driving on the southbound section consumed 0.57 L more than driving on the northbound section.

4. COMPARISON OF MANUAL AND CCC DRIVING TESTS

It was clearly demonstrated that using CCC resulted in significant fuel savings when compared to manual driving. Additionally, using CCC on a downhill section saved more fuel than using it on an uphill section. Consequently, further tests were conducted using simulation to test how the fuel economy would change if an ECC was used on the southbound and northbound lanes of the test section.

For the comparison, the ECC was used to simulate eco-driving on the identical southbound and northbound sections of I-81 [8]. Specifically, the roadway profiles, which included the topographical information of the study sections, were used during the simulation. The operation of the system is conceptually illustrated in Figure 5. First,

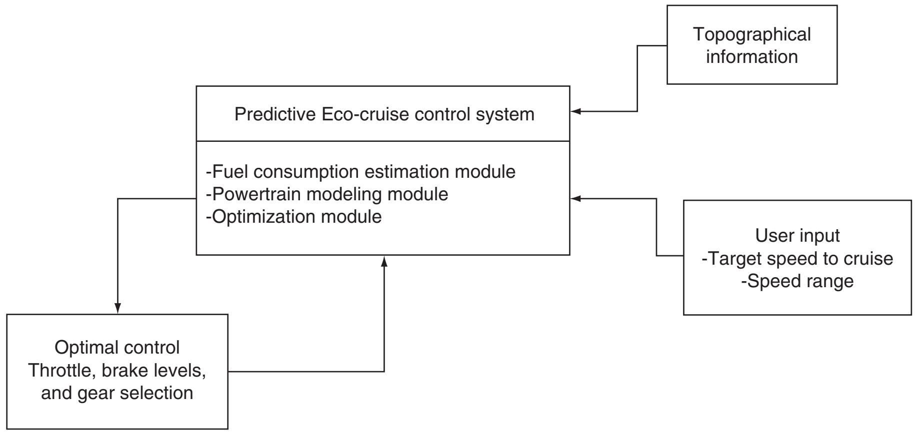

Figure 5. Conceptual diagram of the predictive ECC system

future topographical information is fed to the system from a navigational mapping system. Second, the user sets a target cruise speed and a speed range (or speed window) within which the vehicle operates. Next, the system generates an optimal plan for throttle, braking levels, and gear selections across a predefined distance using dynamic programming (DP) by discretizing the solution space of speed and distance. The system then updates these procedures during the entire trip.

The ECC system comprises of three building blocks: a powertrain module, a fuel consumption module, and an optimization module. These modules are closely connected with each other so that the system can simulate the vehicle operations under the given topographical information and characteristics, estimate the fuel consumption rates based on the vehicle operating conditions, and find an optimal control plan that minimizes the vehicle fuel consumption while satisfying the preset minimum vehicle speed levels using the optimization module. The VT-CPFM was used to estimate instantaneous fuel consumption rates within the fuel consumption module. Dijkstra's shortest path algorithm and a heuristic optimization algorithm were used in the optimization module to find the optimal control strategy. Additional descriptions of the individual modules are available in the literature [8].

The powertrain module was calibrated using the vehicle specifications of each vehicle. The VT-CPFM was also calibrated using the vehicle specifications and was validated using the fuel consumption rates measured in this study in order to estimate second-by-second fuel consumption rates. The calibrated VT-CPFMs were proven to provide reliable fuel consumption estimates close to the field measurements with marginal errors. Figure 6 shows an example of the instantaneous fuel consumption rate comparisons. The figure clearly demonstrates a good match between the field measurements and model estimates.

For an unbiased comparison, the fuel consumption rates of manual driving and CCC driving were also estimated using the VT-CPFM models rather than using the field-

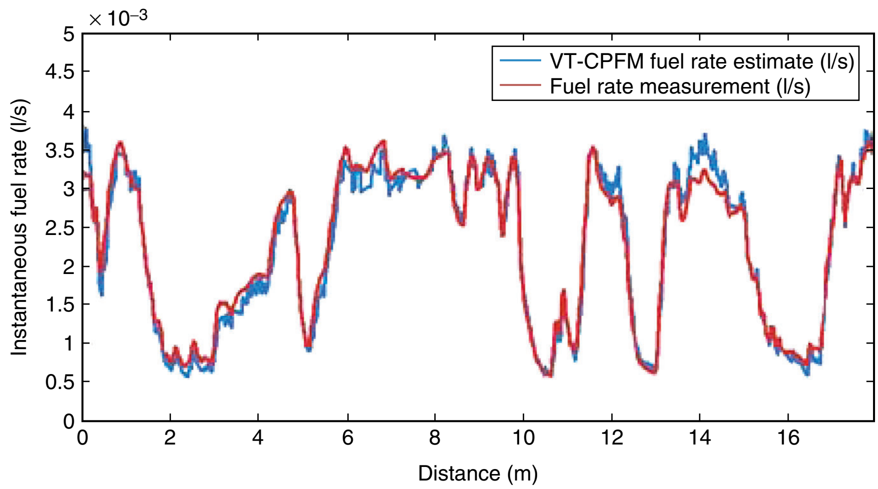

Figure 6. Fuel consumption measurements and VT-CPFM estimates for the Chevy Malibu

measured fuel consumptions. Since the instantaneous power level is required to run the VT-CPFM model, the power levels were calculated from the field test profiles of individual vehicles for manual driving and CCC driving. Then, the power levels of the ECC driving were simulated and fed to the VT-CPFM models to calculate the second-by-second fuel consumption rates. The latter estimates were then aggregated and compared to the simulation results of the ECC driving.

The aggregated fuel consumption estimates are presented in Table 7. As can be seen, the fuel savings of predictive ECC driving ranged from 7.9% to 15.7% when compared

Table 7. Fuel savings of predictive ECC driving

		Field Consumption (L)							ECC
		Manual Driving			CC				Savings
Section	Vehicle	LB*	UB*	Mean	LB	UB	Mean	ECC (L)	(%)
I-81 South	Mercedes R350	2.19	2.24	2.22	2.15	2.16	2.15	1.93	10.5%
	Chevy Tahoe	2.39	2.44	2.42	2.37	2.44	2.40	2.03	15.3%
	Chevy Malibu	1.35	1.38	1.36	1.34	1.38	1.36	1.20	11.9%
	Hybrid Chevy Malibu	1.51	1.59	1.55	1.45	1.52	1.49	1.30	12.7%
	Toyota Camry	1.32	1.34	1.33	1.32	1.4	1.36	1.16	14.9%
I-81 North	Mercedes R350	1.45	1.51	1.48	1.42	1.44	1.43	1.31	8.4%
	Chevy Tahoe	1.66	1.69	1.68	1.64	1.72	1.68	1.42	15.7%
	Chevy Malibu	0.98	0.99	0.99	0.97	1.02	1.00	0.92	7.9%
	Hybrid Chevy Malibu	1.13	1.16	1.15	1.04	1.08	1.06	0.96	9.3%
	Toyota Camry	0.99	1.01	1.00	1.00	1.03	1.02	0.89	13.0%

*LB and UB stand for lower bound and upper bound.

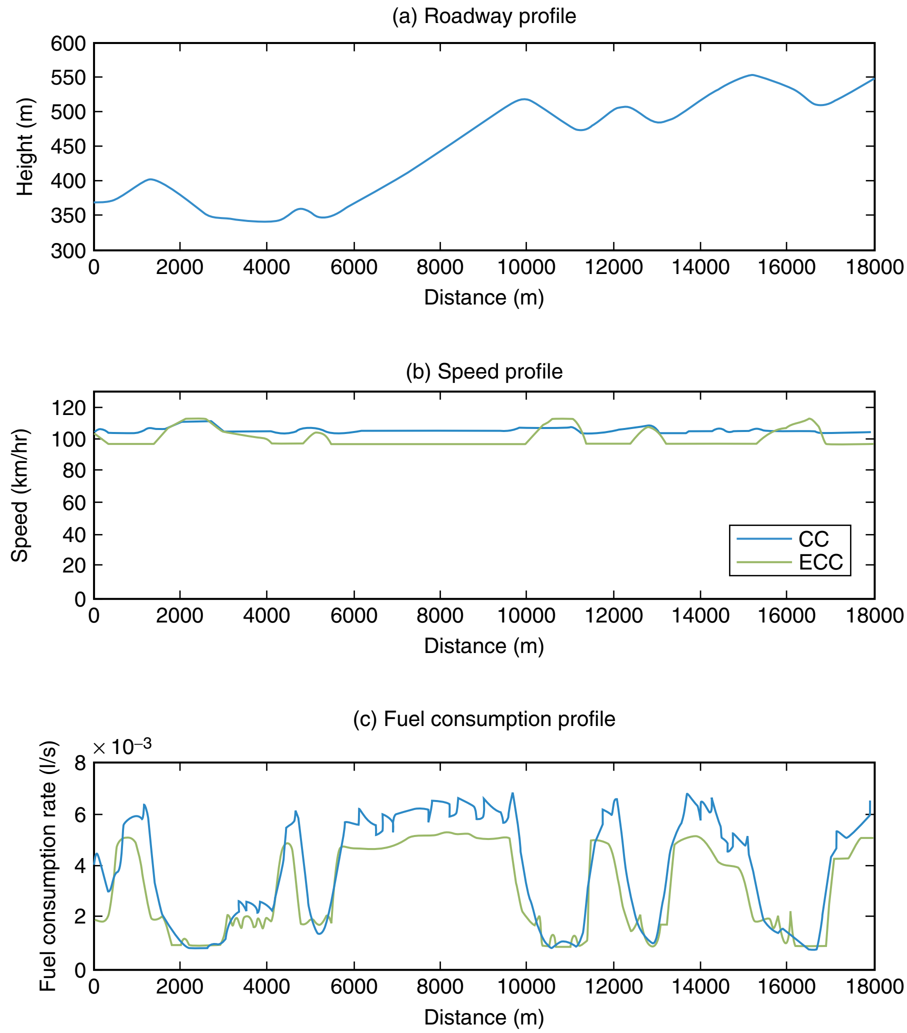

Figure 7. Speed and fuel consumption profiles for ECC and CCC Systems

to CCC driving. Specifically, the predictive ECC was most efficient for the Chevy Tahoe. The underlying fuel-saving logic can be explained by comparing the speed profiles of the ECC and CCC systems. As can be seen in Figure 7, CCC driving attempts (with some errors) to maintain the target speed of 65 mph (104 km/h) regardless of the preceding gradients, while the ECC adjusts the speed and responds to the gradients so that the vehicle can maintain lower speeds on the uphill sections and higher speeds on the downhill sections.

The travel times for ECC driving on the southbound and northbound sections were 651 seconds and 682 seconds, respectively. Those travel times were 6.2% greater for the southbound section and 3.2% greater for the northbound section than those of CCC driving. Given that the average fuel savings of ECC driving were 13.1% for the southbound section and 10.9% for the northbound section, the fuel savings were more significant than the increased travel times.

5. STUDY CONCLUSIONS

The research presented in this paper investigated the fuel efficiency of a CCC system compared to manual driving using field data gathered along a 24-km section on Interstate 81. The test section was selected given that it comprises various uphill and downhill sections. The study found that CCC driving improves vehicle fuel efficiency compared to manual driving although there were some variations in the differences depending on the driver, the vehicle, and the direction of travel. The average fuel economy enhancement across all the field tests was 3.3%, however this difference was not found to be statistically significant at a 5 percent significance level. The results demonstrate that CCC driving is more efficient on downhill versus uphill sections. In addition, the study demonstrates that an ECC system can produce fuel savings ranging between 8 and 16 percent with increases in travel times ranging between 3 and 6 percent. These benefits appear to be largest for heavier vehicles (SUVs).

ACKNOWLEDGEMENTS

This work was partially sponsored by the Tran *LIVE* University Transportation Center and the Mid-Atlantic University Transportation Center.

REFERENCES

[1] B. T. W. Lin and S. L. Hwang, "Effect prediction of time-gaps for adaptive cruise control (ACC) and in-vehicle tasks on bus driver performance," *Safety Science,* vol. 50, pp. 68–75, Jan 2012.

[2] D. Ellis. (2007). *4 gas-saving myths*. Available: http://money.cnn.com/2007/05/09/pf/gas_myths/index.htm

[3] K. Ahn, H. Rakha, A. Trani, and M. Van Aerde, "Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels," *Journal of Transportation Engineering*, vol. 128, pp. 182–190, 2002.

[4] Natural Resources Canada. *Auto$mart Thinking - Driving and Maintaining Your Vehicle*. Available: http://oee.nrcan.gc.ca/transportation/personal/driving/2578

[5] Drew Technologies Inc., "DashDAQ Series II - Instruction Manual," ed, 2010.

[6] H. Rakha, M. Van Aerde, K. Ahn, and A. A. Trani, "Requirements for evaluating traffic signal control impacts on energy and emissions based on instantaneous speed and acceleration measurements," *Transportation Research Record. n 1738 2000,* pp. 56–67 00-1133, 2000.

[7] H. Rakha, I. Lucic, S. H. Demarchi, J. R. Setti, and M. Van Aerde, "Vehicle dynamics model for predicting maximum truck acceleration levels," *Journal of Transportation Engineering*, vol. 127, pp. 418–425, 2001.

[8] S. Park, H. Rakha, K. Ahn, and K. Moran, "Predictive Eco-cruise Control System: Model Logic and Preliminary Testing," *Presented at 91th Annual Meeting of the Transportation Research Board, Washington D.C.,* 2012.